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Letter to the Editor

Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes

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ABSTRACT

Desalination technologies improve water quality, greatly reduce water shortage problems, and improve quality of life and economic status. Two main technologies are currently used in water desalination: thermal (phase-change) processes and membrane processes. The primary thermal distillation processes include multistage flash distillation (MSF), multi-effect distillation (MED), and vapor compression (VC). The VC process encompasses two types: mechanical (MVC) and thermal (TVC). The common membrane desalination processes include reverse osmosis (RO) and electrodialysis (ED and EDR).

Energy cost, operational and maintenance cost, and capital investment are the main contributors to the water production cost of any of these processes. The energy cost is responsible for about 50% of the produced water cost. For thermal distillation processes (MSF, MED, and TVC), two energy forms are required for the operation: (1) low-temperature heat, which represents the main portion of the energy input and is usually supplied to the system by a number of external sources (e.g., fossil fuel, waste energy, nuclear, solar) and (2) electricity, which is used to drive the system's pumps and other electrical components. For the MVC thermal distillation process, only electricity is needed. For membrane processes (RO and ED), only electricity is required as an energy input.

Renewable energy systems such as solar thermal, solar photovoltaic, wind, and geothermal technologies are currently used as energy suppliers for desalination systems. These renewable resources are now a proven technology and remain economically promising for remote regions, where connection to the public electric grid is either not cost effective or feasible, and where water scarcity is severe. As the technologies continue to improve, and as fresh water becomes scarce and fossil fuel energy prices rise, renewable energy desalination becomes more viable economically.

The technical features, energy consumption, environmental considerations, and potential of renewable energy use in driving the main desalination processes are reviewed and analyzed in this paper. The current and projected costs of water produced from conventional and renewable-energy-driven processes are discussed and compared.

1. Conventional desalination processes

Desalination technologies are categorized as thermal (phase-change) and membrane desalination, and these are further divided into subgroups. The main thermal distillation technologies are multi-stage flash (MSF), multi-effect distillation (MED), vapor compression (VC), whereas the main membrane technologies are reverse osmosis (RO) and electro-dialysis (ED and EDR) [1].

1.1. Thermal distillation technologies

1.1.1. Multi-stage flash

MSF distillation is an energy-intensive process that requires both thermal and electrical energy. The thermal energy is in the form of low-pressure bleed steam (1 to 3 bars) for the feed-brine heating, and medium-pressure steam for the ejectors to generate the required vacuum in different sections of the unit. The electrical energy is required for driving the unit's various pumps such as recycle, cooling water, distillate product, brine blow down, condensate, and chemical dosing pumps. MSF units typically range from 10,000 to 35,000 m^3/day and consist of a series of stages, ranging from 4 to 40 each, with successively lower temperature and pressure that cause flash evaporation of the hot brine followed by condensation as fresh water. In this process, the feed seawater moves in heat exchangers through the stages and gains some heat that helps to reduce the external thermal energy needed for hot brine and also to condense the water vapor for collection as fresh water in each stage. External heat from fossil-fuel boilers, power-plant waste heat, nuclear reactor, renewable energy, or any other heating source is supplied to the intake preheated seawater to raise its temperature to the required top brine temperature of 90° to 110 °C. The heated brine water is then moved through stages that are held at successively lower pressure in which a small amount of water flashes to vapor in each stage and the remaining brine flows to the next stage for further flashing until it is finally discharged. The vapor from each stage is condensed and collected as fresh water [2,3]. Fig. 1 shows a schematic diagram of the MSF unit. Flashing of the steam forms scales and deposits on the tubes, so periodic cleaning and removal is required. MSF is currently the second-most desalination process installed worldwide after the RO process.

1.1.2. Multi-effect distillation

The MED process consists of a series of stages (usually from 2 to 16) that are maintained at decreasing levels of pressure.

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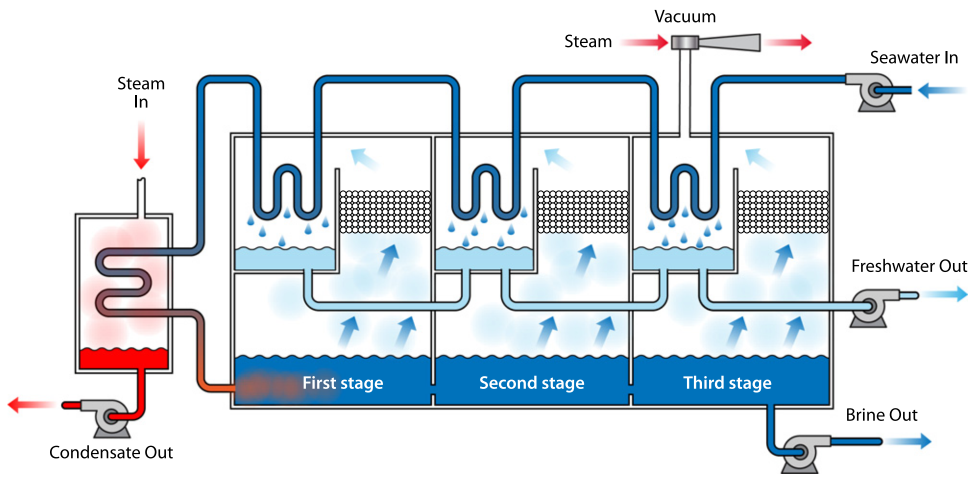

Fig. 1. Schematic diagram of MSF unit.

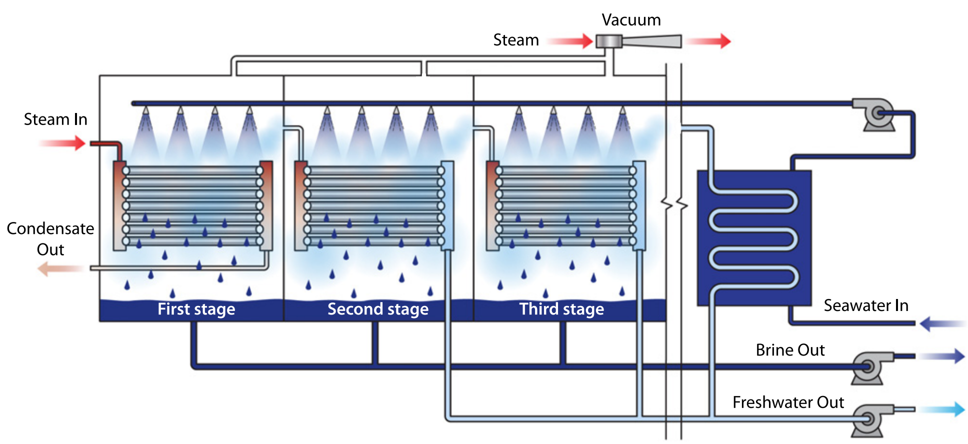

Fig. 2. Schematic diagram of MED unit.

External heat from a fossil-fuel boiler, power-plant waste heat, solar, or other sources is supplied to increase the brine temperature of the first stage to around 70 °C, to be used to evaporate some of the brine inside the stage that is kept at low pressure. The water vapor produced from the stage is transferred inside a tube to the next heating stage for boiling additional seawater, which produces water vapor in a series fashion. MED units are generally built at capacities of 600 to 30,000 m^3/day and the design is based on two arrangements: the vertical tube in which the seawater boils in a thin film flowing inside the tube and vapor condenses on the heat-transfer tubes, and horizontal tube where the seawater feed is sprayed on the outer surface of the tubes and vapor flows inside the horizontal tubes, where it condenses to produce water. Fig. 2 shows a schematic diagram of the MED unit. The earliest distillation plants used MED, but MSF displaced it due to its lower cost and less tendency to scale [4]. In the past few years, the interest in the MED process has been renewed and appears to be gaining market share.

1.1.3. *Mechanical vapor compression*

Distillation plants using vapor compression rely on the heat generated by the compression of water vapor to evaporate salt water, and two methods are employed—mechanical vapor compression (MVC) and thermo vapor compression (TVC). The feed water enters the VC process through a heat exchanger, and vapor is generated in the evaporator and compresses by mechanical (MVC) or thermal (TVC) means. Compression the vapor raises its temperature by a sufficient amount to serve as the heat source. The concentrated brine is removed from the evaporator vessel by the concentrate reticulating pump. This flow is then split, and a portion is mixed with the incoming feed and the remainder is pumped to the waste. Fig. 3 show both types. MVC use electricity to drive the compressor, whereas in TVC a steam jet creates the lower pressure. These units are usually used in small- and medium-sized applications. MVC capacity ranges between 100 and 3000 m^3/day, and TVC capacity ranges between 10,000 and 30,000 m^3/day [5].

1.2. *Membrane desalination technologies*

1.2.1. *Reverse osmosis*

Reverse osmosis (RO) is a form of pressurized filtration in which the filter is a semi-permeable membrane that allows water, but not salt, to pass through. This yields permeated fresh water and leaves a concentrated solution on the high-pressure side of the membrane. It has four subsystems: (1) pre-treatment, (2) high-pressure pump, (3) membrane, and (4) post-treatment. Feed-water pre-treatment involves filtration, sterilization, and addition of chemicals to prevent scaling and biofouling. The high-pressure pump generates the pressure needed to force the water to pass through the membrane; therefore, the energy needed is electricity to drive the pumps. The pressure needed for desalination ranges from 17 to 27 bars for brackish water and from 55 to 82 bars for seawater. The membranes are designed to yield a permeate water of about 500 ppm and made in a variety of configurations. Several types of membrane are available

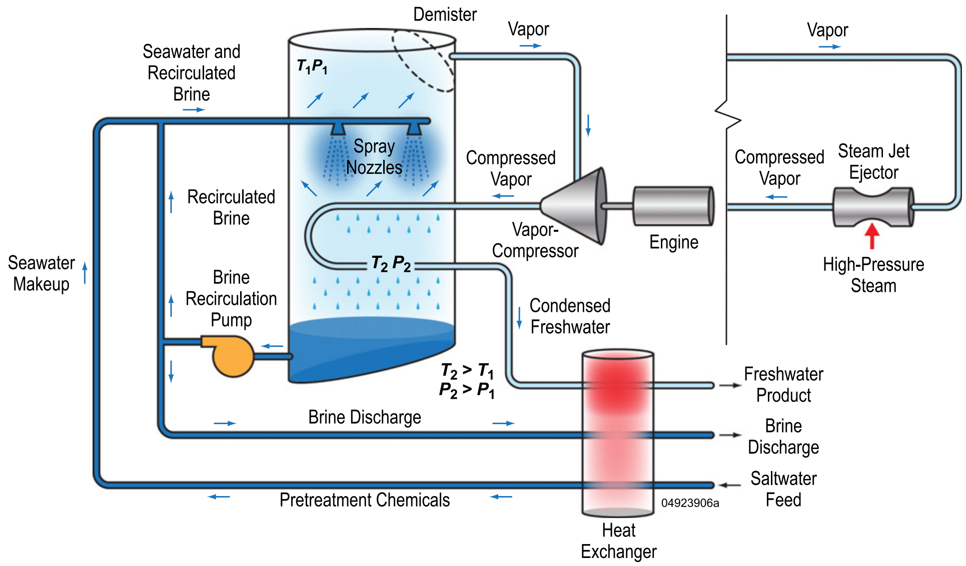

Fig. 3. Schematic diagram of VC (MVC and TVC) units.

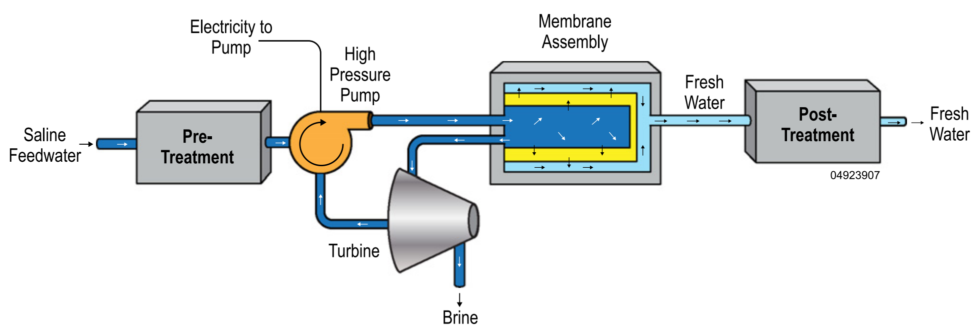

Fig. 4. Schematic diagram of RO system.

in the market, with the two most commonly used ones being spiral-wound and hollow fine fiber. The post-treatment removes gases such as hydrogen sulfide and adjusts pH. Fig. 4 is a schematic diagram of an RO system. RO is a mature technology that is the most commonly used desalination technique. Its installed capacity ranges between 0.1 m^3/day (used in marine and household applications) to 395,000 m^3/day (for commercial applications) [6–12].

1.2.2. *Electro-dialysis and electro-dialysis reversal*

Electrodialysis (ED) is an electrochemical separation process that operates at atmospheric pressure and uses direct electrical current to move salt ions selectively through a membrane, leaving fresh water behind. The ED unit consists of the following components: pretreatment system, membrane stack, low-pressure circulation pump, direct-current power supply (rectifier or photo-voltaic system), and post-treatment system. The operational principle of ED is as follows: electrodes (generally constructed from niobium or titanium with a platinum coating) are connected to an outside source of direct current in a container of salt water containing an ion-selective membrane connected in parallel to form channels. When brackish water flows between these channels and electricity is charging the electrodes, positive salt ions travel through the cation-permeable membrane toward negative electrodes, and negative salt ions travel through the anion-permeable membrane to the positive electrode, which results in the removal of salinity from the water. This creates alternating channels—a concentrated channel for the brine and a diluted channel for the product fresh water [9,12]. An ED plant's typical capacity ranges from 2 to 145,000 m^3/day. Fig. 5 shows the schematic diagram of an ED unit. In EDR, the polarity of the electrodes is switched periodically. The concentrate stream is then converted to the feed stream and the feed stream becomes the concentrate stream. Reversing the flow increases the life of the electrodes and helps to clean the membranes. When the membranes

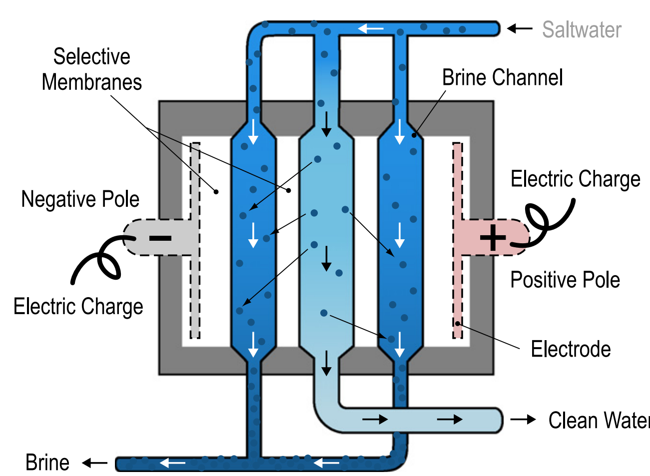

Fig. 5. Schematic diagram of ED unit.

are operated in the same direction all the time, precipitant can build up on the concentrate sides [13].

2. Energy requirement for desalination processes

2.1. Minimum energy requirement for desalination

All desalination processes are energy intensive and share a common minimum energy requirement for driving the separation of a saline solution into pure water and concentrated brine. It is independent of the detailed technology employed, exact mechanism, or number of process stages. The concept of minimal energy for the separation process is well established in thermodynamics. The solute movement is wholly determined by fluctuations of thermal collisions with nearby solvent molecules. The minimum work needed is equal to the difference in free energy between the incoming feed (i.e., seawater) and outgoing streams (i.e., product water and discharge brine). Different methods were used to calculate the minimum energy requirement of water desalination. Using the van't Hoff formula for normal seawater of salinity equal to 33,000 ppm at 25 °C, the minimum work has been calculated as 0.77 kW h/m^3 [14].

2.2. Actual energy requirement of main desalination processes

The actual work required is likely to be many times the theoretically possible minimum. This is due to the extra work required to keep the process going at a finite rate, rather than to achieve the separation. Currently, desalination plants use 5 to 26 times as much work as the theoretical minimum, depending on the type of process used. Due to this intensive energy consumption, there is a need to make desalination processes as energy efficient as possible by improving the technology and economies of scale. RO, ED, and VC systems use electricity as a primary source of energy, whereas MSF, MED, and TVC systems use thermal energy as a primary source and electricity to drive associated pumps as a secondary source. Electricity could be generated from fossil fuel (coal, oil, and gas), renewable energy, and nuclear sources. Thermal energy could be produced from fossil-fuel-fired boilers, power-plant waste heat, renewable energy sources, and industrial-waste heat sources.

3. Energy consumption of the main processes

3.1. Distillation processes

Two types of energy – low-temperature heat and electricity – are required for most distillation processes (MSF, MED, and TVC). The low-temperature heat represents the main portion of the energy input and the electricity is used to drive the system's pumps.

For the MVC process, only electricity is required. All thermal processes are equipped with condenser-tube bundles and numbers of large pumping units, including pumps for seawater intake, distillate product, brine blow down, and chemical dosing. The simplest distillation technique, single-stage evaporation, consumes a tremendous amount of energy. Boiling water requires around 650 kW h/m^3 of product, depending slightly on the evaporation temperature. The main evaporation techniques (MSF and MED) have overcome this obstacle by reusing the energy consumption through multiple stages. The efficiency of the low-temperature heat is usually identified by one of two equivalent parameters: (1) the gain output ratio (GOR), which is a measure of how much thermal energy is consumed in the desalination process, and is defined as the ratio of the mass of distillate (kg) to the mass (kg) of the input steam, and (2) the performance ratio (PR), which is the mass of distillate (kg) per 2326 kJ.

3.1.1. Energy consumption in MSF process

The energy consumption of the MSF depends on several factors: maximum temperature of the heat source, temperature of the heat sink, number of stages, salt concentration in the flashing brine solution, geometrical configuration of the flashing stage, construction materials, and design configuration of heat-exchange devices. Therefore, the energy consumption of the MSF unit can be reduced by increasing the GOR (or PR), number of stages, and the heat-transfer area [15–21]. The MSF process operates at a top brine temperature (TBT) in the range of 90° to 110 °C. An increase of TBT increases the flash range, which, in turn, increases the production rate and improves the performance. However, selection of TBT is limited by the temperature to which the brine can be heated before serious scaling occurs. MSF commercial manufacturers provide a GOR design range between 8 and 12 $kg_{distillate}/kg_{steam}$ depending on the steam feed temperature [15]; but the reported typical GOR in the Arab Gulf countries' plants ranges between 8 and 10, and the typical PR ranges between 3.5 and 4.5 $kg_{distillate}$/MJ [16]. If we use the manufacturers' values, then the thermal energy consumption of an MSF plant ranges between 190 MJ/m^3 (GOR=12) and 282 MJ/m^3 (GOR=8). The electrical energy equivalent to these values based on power plant efficiency of 30% ranges between 15.83 and 23.5 kW he/m^3. The electricity consumption of the pumps ranges between 2.5 and 5 kW he/m^3 therefore, the total equivalent energy consumption of the MSF unit ranges between 19.58 and 27.25 kW he/m^3.

3.1.2. Energy consumption in MED process

The MED process also requires two types of energy—low-temperature heat for evaporation and electricity for pumps. It operates at brine temperatures ranging from 64° to 70 °C. The manufacturers of MED units provide a GOR design ranging from 10 to 16. Typical Arab Gulf countries' MED plants operate at lower GOR values of 8 to 12 [16]. If we use the manufacturers' values, then the thermal energy consumption of MED plants ranges between 145 MJ/m^3 (GOR=16) to 230 MJ/m^3 (GOR=10). The work equivalent to these values based on a power-plant efficiency of 30% ranges from 12.2 to 19.1 kW he/m^3. The total electricity consumption of the pumps ranges from 2.0 to 2.5 [15]; therefore, the total equivalent energy consumption of the MSF units ranges from 14.45 to 21.35 kW he/m^3.

3.1.3. Energy consumption in MVC and TVC processes

MVC needs electrical or mechanical energy only. It operates at a maximum TBT around 74 °C, with electrical energy consumption ranging from 7 to 12 kW he/m^3 [15]. For TVC, both low-temperature heat and electricity are needed. At TBT ranges from 63° to 70 °C, GOR of around 12, a heat input of 227.3 MJ/m^3 (14.56 kW he/m^3), and electricity consumption of 1.6–1.8 kW he/m^3 are required [15]. Therefore, the total energy consumption of the TVC process is about 16.26 kW he/m^3.

3.2. Membrane processes

Electricity is the only form of energy consumed in the membrane processes. For the RO process, AC electricity is consumed to drive the different pumps, whereas DC electricity is consumed in the ED electrodes and AC or DC electricity is consumed to drive the ED pumps.

3.2.1. Energy consumption in RO process

Electricity is the only required form of energy in the RO process. Energy consumption of the RO unit depends mainly on the salinity of the feed water and the recovery rate. The osmotic pressure is related to the total dissolved solids (TDS) concentration of the feed water; therefore, high-salinity water requires a higher amount of energy due to higher osmotic pressure. RO unit sizes vary from a very small unit with a capacity of 0.1 m^3/day to a 395,000 m^3/day plant. The average reported energy consumption ranges from 3.7 to 8 kW h/m^3 [15,21,22]. The consumption may exceed 15 kW h/m^3 for very small sizes units. For a typical size of seawater RO (SWRO) unit of 24,000 m^3/day, the electricity consumption ranges from 4 to 6 kW h/m^3 with an energy recovery (ER) system for seawater. Low pressure is needed to desalinate brackish water; therefore, different membranes are used and much higher recovery ratios are possible, which makes energy consumption low. For a brackish-water RO (BWRO) unit, the electrical energy consumption ranges from 1.5 to 2.5 kW h/m^3 [15,21,22].

3.2.2. Energy consumption in ED process

Electricity is the only form of energy required for the ED process. DC electricity is used for ED electrodes, and AC or DC electricity is used to drive the pumps. For low salinity (<2500 ppm), the electricity consumption of an ED unit ranges from 0.7 to 2.5 and 2.64 to 5.5 kW h/m^3 for a salinity range between 2500 and 5000 ppm, respectively [23,24].

3.3. Comparison of energy consumption between the main desalination processes

Different factors have influence on energy consumption, including: plant capacity, unit design, materials used, and the seawater feed stream quality to the unit. It should be noted that the energy consumption in distillation processes (MSF, MED and VC) is not influenced by the salt concentration in the feed water, whereas it is highly influenced by the salt concentration in the membrane processes (RO and ED). If we compare the energy consumption of the most commonly used methods in seawater desalination (MSF, MED, and RO), we notice that the distillation processes (MSF and MED) require higher energy than RO process. It is around 19.58 to 27.25 kW he/m^3 of water for MSF and 14.45 to 21.35 kW he/m^3 of water for MED, in contrast to 4 to 6 kW he/m^3 of water for the SWRO process with an ER system. This is due to two main reasons: the high energy need for water vaporization, and the continuous improvement in the technology of the RO process membrane, which resulted in lower power consumption. For brackish-water desalination, the two most commonly used methods are RO and ED. RO is generally believed to be more cost effective when TDS is more than 5000 ppm, whereas ED is more cost effective for TDS feed concentrations less than 5000 ppm. The electrical energy consumption of BWRO is around 1.5 to 2.5 kW h/m^3. The ED consumptions range from 0.7 to 2.5 kW h/m^3 for less than 2500 ppm, and 2.64 to 5.5 kW he/m^3 for more than 2500 ppm. Table 1 presents the reported average consumption of the main desalination processes.

4. Economics of desalination processes

Many factors enter into the economics of desalination. Among these are the following: intake water quality, plant capital cost, energy cost, labor and maintenance cost, concentrate disposal cost, and financing interest rate. Energy is the largest segment of water production cost of all desalination systems. Main distillation processes (MSF, MED, and TVC) use low-temperature heat for vaporization and electrical energy for water pumping. The energy cost of thermal distillation seawater plants is close to 60% of water production costs. In cogeneration plants, where the low-temperature heat is supplied from the waste heat of the turbine exhaust, the energy cost will be much less. The main membrane desalination process (RO) relies heavily on electrical energy, and its cost is around 44% of the total water costs.

4.1. Distillation processes economic

Distillation plants are used to desalinate seawater and usually have a large capacity. Ref. [20] is a comprehensive review of the literature for estimating the cost of fresh water. For MSF plants with a production capacity between 23,000 and 528,000 m^3/day, the reported water production cost was between 0.52 and 1.75 US$/$m^3$ [25–48]. For MED plants with production capacity of more than 90,000 m^3/day, the reported cost ranged between 0.52 and 1.01 US$/$m^3$. For medium MED capacities of 12,000 to 55,000 m^3/day, the cost varies between 0.95 and 1.95 US$/$m^3$ [25–48]. VC is usually used in small-capacity systems. For systems of capacity of around 1000 m^3/day, the reported cost ranged between 2.0 and 2.60 US$/$m^3$ [25–48].

4.2. Membrane processes economic

Due to improved membrane technology in recent years, RO water production costs have decreased. For large SWRO plants with capacities ranging between 100,000 and 320,000 m^3/day, the reported water production cost ranged between 0.45 and 0.66 US$/$m^3$. For medium SWRO plants with capacities ranging between 15,000 and 60,000 m^3/day, the reported water production cost ranged between 0.48 and 1.62 US$/$m^3$. For smaller capacity SWRO units of 1000 to 4800 m^3/day, the cost ranged between 0.7 and 1.72 US$/$m^3$ [25–48]. For brackish water (less than 10,000 ppm), RO and ED (EDR) are the most economic methods of water desalination, and both could be used. For TDS higher than 5000 ppm, the RO system is the most economic; but

Table 1
Energy consumption of the main desalination processes.
Sources: Refs. [14–24].

Properties	MSF	MED	MVC	TVC	SWRO	BWRO	ED
Typical unit size (m^3/day)	50,000–70,000	5,000–15,000	100–3,000	10,000–30,000	Up to 128,000	Up to 98,000	2–145,000
Electrical energy consumption (kW h/m^3)	2.5–5	2–2.5	7–12	1.8–1.6	4–6 with energy recovery	1.5–2.5	2.64–5.5
Thermal energy consumption (MJ/m^3)	190–282	145–230	None	227	None	None	None
Equivalent electrical to thermal energy (kW h/m^3)	15.83–23.5	12.2–19.1	None	14.5	None	None	None
Total electricity consumption (kW h/m^3)	19.58–27.25	14.45–21.35	7–12	16.26	4–6	1.5–2.5	2.64–5.5, 0.7–2.5 at low TDS
Product water quality (ppm)	≈ 10	≈ 10	≈ 10	≈ 10	400–500	200–500	150–500

for lower ppm, or when high recovery is required, ED is the more cost-effective desalination system. The water production cost of large-capacity BWRO plants (40,000 to 46,000 m^3/day) range from 0.26 to 0.54 US\$/m^3, whereas the water production cost of ED plants range from 0.6 to 1.05 US\$/m^3, with cost depending greatly on the salinity of the feed water [25–48].

4.3. Water cost comparison of the main processes

Even though distillation systems produce water with very low ($\approx$ 10 ppm) TDS compared to 400 to 500 ppm in the RO system, improved technology has resulted in developing membranes that require less pressure (less energy), longer life, and reduced cost. This has made RO a more economical process than other desalination methods. This is not the case when the low-temperature heat is supplied from the byproduct of the electricity power plant, any waste heat or economically available solar source, or when we want to desalinate a very salty water of more than 60,000 ppm. The economics can then shift in favor of the distillation process. Table 2 presents the reported average total water production cost of the main desalination processes.

Table 2
Average water production cost of the main desalination processes.
Source: Refs. [25–48].

Type of process	Type of water	Cost of water (US\$/m^3)
MSF	Seawater	
23,000–528,000 m^3/day		0.56 to 1.75
MED	Seawater	
91,000–320,000 m^3/day		0.52–1.01
		0.95–1.5
12,000–55,000 m^3/day		2.0–8.0
Less than 100 m^3/day		
VC	Seawater	
30,000 m^3/day		0.87–0.95
1,000 m^3/day		2.0–2.6
RO	Seawater	
100,000–320,000 m^3/day		0.45–0.66
15,000–60,000 m^3/day		0.48–1.62
1,000–4,800 m^3/day		0.7–1.72
RO	Brackish water	
Large capacity: 40,000 m^3/day		0.26–0.54
Medium: 20–1,200 m^3/day		0.78–1.33
Very small: few m^3/day		0.56–12.99
ED	Brackish water	
Large capacity		0.6
Small capacity		1.05

5. Renewable energy coupled desalination systems

Using renewable energy sources (RES) to drive desalination technologies is a viable way to produce fresh water in many locations today. Particularly promising are renewable-energy-powered desalination systems for remote regions, where the connection to the public electrical grid is either not cost effective or not feasible, and where water scarcity is severe. As the technologies continue to improve – and as fresh water and cheap conventional sources of energy become scarcer – RES desalination will become even more attractive. Several solar, wind, and geothermal or hybrid solar/wind desalination plants have been installed; most of them are demonstration projects and consequently are of small capacity.

5.1. Solar thermal coupled desalination

Solar energy can be converted to thermal or electrical energy. Thermal energy can be obtained using solar stills or solar thermal collection systems. Electrical energy can be produced from solar photovoltaic (PV) conversion or solar thermal power plants.

5.1.1. Direct solar thermal distillation/solar stills

This technology has been in use for many decades and its technology is based on the principles of the greenhouse effect. A solar still consists of a shallow basin covered by a transparent roof acting as a condenser. Solar radiation is trapped in the still, causing the evaporation of water. The average production of the solar still ranges from 4 to 6 l/day. Stills have undergone many modifications and improvements, including changing the configuration and flow pattern to enhance the heat-transfer rate, using wicks and different layers of glass cover, and coupling the still with solar collectors. Using solar still systems to provide fresh

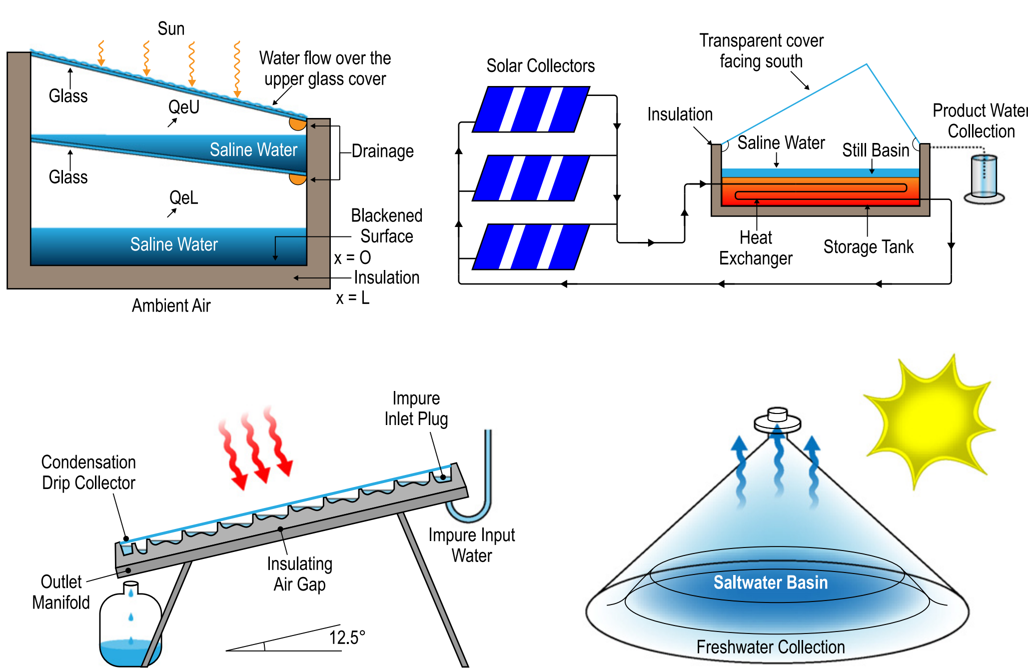

Fig. 6. Several types of solar still.

water becomes a suitable and competitive solution for many remote and rural regions, especially when small quantities of water for human consumption are needed [49–51]. Fig. 6 shows several solar still diagrams [49].

5.1.2. Solar pond

Solar ponds combine solar energy collection and the large capacity of long-term (seasonal) thermal storage. Solar ponds are able to store heat due to their unique chemically stratified nature. There are three layers in a solar pond: (1) the upper or surface layer, called the upper convection zone, (2) the middle layer, which is the non-convection zone or salinity gradient zone, and (3) the lower layer, called the storage zone or lower convection zone. Salinity is relatively constant in the upper and lower convection zones, and it increases with depth in the non-convection zone. Although the top temperature is close to ambient, a temperature of 90 °C can be reached at the bottom of the pond where salt concentration is highest. The large storage capacity of solar ponds can be useful for continuous operation of MED, MSF, or TVC desalination plants or to drive a Rankine-cycle engine to generate electricity for RO, MVC, and ED desalination plants. Solar ponds provide many advantages to power desalination plants, including: the large capacity of heat storage allows solar ponds to power desalination units during cloudy days and nighttime; the waste reject brine from desalination units could be used to build the solar pond; and when the solar pond is used for electricity generation, the rejected heat from the power plant could be used in a thermal desalination plant [49]. Several plants have been implemented that couple a solar pond to an MSF process [49,53]: Margarita de Savoya, Italia (50–60 m^3/day), Islands of Cape Verde (300 m^3/day), Tunisia (8.6×10^{-3} m^3/h), and El Paso, Texas (19 m^3/day). In addition, several SP/MED plants were implemented such as the plants at the University of Ancona, Italy (30 m^3/day) and near the Dead Sea (3000 m^3/day). Fig. 7 shows a schematic diagram of a solar-pond/MED distillation plant.

5.1.3. Solar multi-effect humidification

Multi-effect humidification (MEH) consists of an evaporator where air is humidified and a condenser where distilled water is recovered. The process occurs under atmospheric conditions by an air loop saturated with water vapor. MEH units are very compact and fall into two types of processes: open-water/closed-air cycle, and open-air/closed-water cycle. Fig. 8 is a schematic of both types of MEH systems.

In the first type of MEH unit, air circulates between a humidifier and a condenser using natural or forced-draft circulation. Saline water feed is preheated in the condenser by the latent-heat condensation of water that would have been lost in a single-basin still. The feed water leaving the condenser section is further heated in the solar collector before being sprayed over packing in the humidifier section.

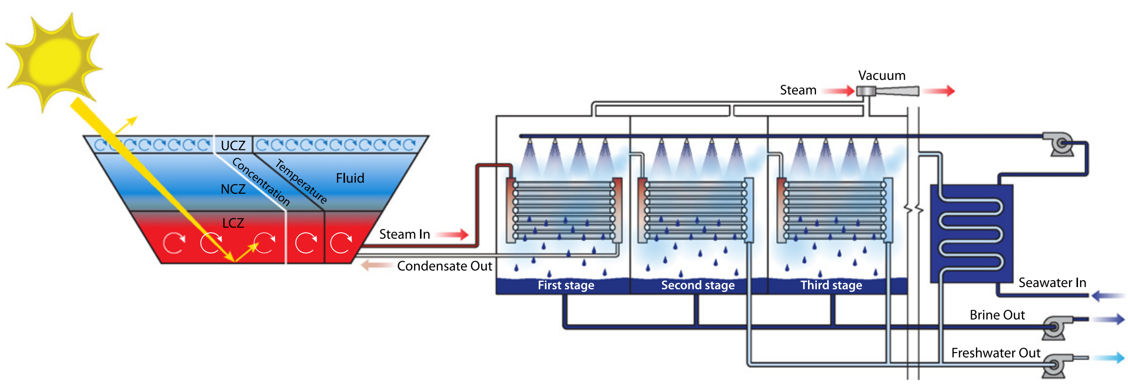

Fig. 7. Solar pond/MED desalination.

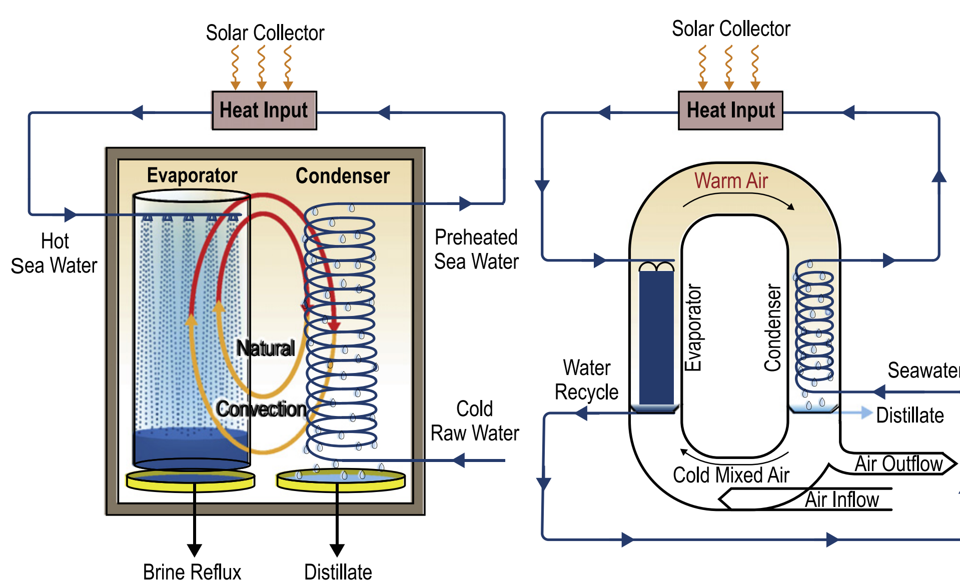

Fig. 8. Schematic diagram of MEH unit.

In the second type of MEH unit, the water heats and humidifies the cold mixed air entering the evaporator. The warm, moist air then enters the condensing section and heats the saline water feed before it is discharged from the system. The MEH principle offers several advantages, such as flexibility in capacity, moderate installation and operating costs, simplicity, and the possibility of using low-temperature energy such as solar energy. Two types of energy – low-temperature heat at about 85 °C and electricity – are required in an MEH process [49,53]. The energy is needed for compensation of sensible heat loss of salt water, pumping salt water, and blowing the air. The largest application of this type of distiller is implemented in Dubai, UAE, and has been operating since 2008. The system consists of a 156-m^2 absorber area and 4.8 kW of PV panels.

5.1.4. Solar membrane distillation

Membrane distillation (MD) is a separation/distillation technique, where water is transported between a "hot" and "cool" stream separated by a hydrophobic membrane—permeable to water vapor only, which excludes the transition of liquid phase and potential dissolved particles. The exchange of water vapor relies on a small temperature difference between the two streams, which results in a difference in vapor pressure, leading to the transfer of the produced vapor through the membrane to the condensation surface. Fig. 9 is a typical schematic of the MD process. In the MD process, the seawater passes through the condenser usually at about 25 °C and leaves at a higher temperature; it is then further heated to about 80 °C by an external source such as solar, geothermal, or industrial waste. The main advantages of membrane distillation are its simplicity and the need for only a small temperature difference to operate. However, the temperature difference and recovery rate determine the overall efficiency for this process. Thus, when it is run with a low temperature difference, large amounts of water must be used, which affects its overall energy efficiency. Membrane distillation is a promising process, especially for situations where low-temperature solar, geothermal, waste, or other heat is available. Membrane distillation has many applications, such as producing fresh water, removing heavy metals, and in the food industry. It is not yet commercially available because of the high cost and problems associated with membranes. Most current MD applications are still in the laboratory or small-scale pilot-plant phase [49,52–56]. A comprehensive review of membrane distillation is presented in Ref. [54].

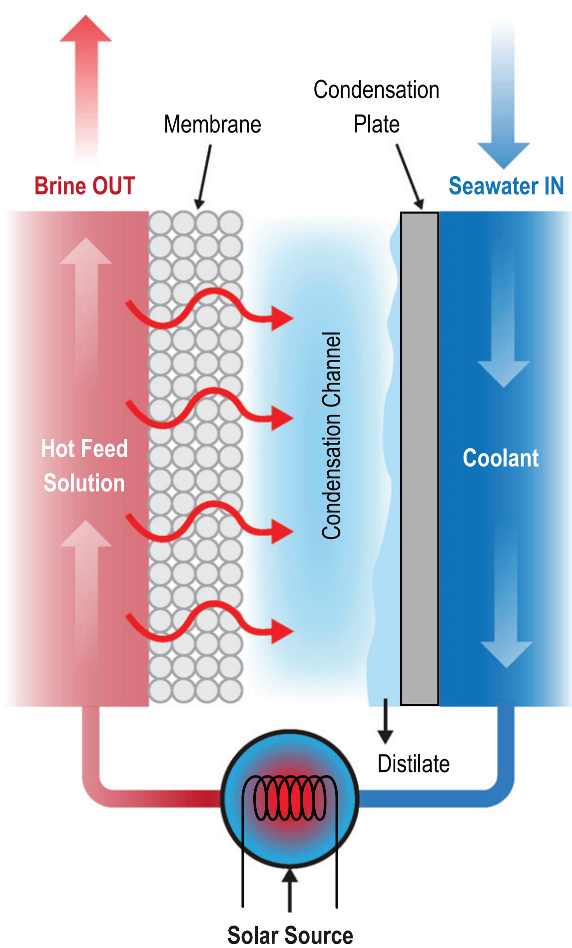

Fig. 9. Schematic diagram of solar MD unit.

5.1.5. Solar thermal CSP

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high-temperature heat for electricity generation within conventional power cycles using steam turbines, gas turbines, or Stirling and other types of engines. For concentration, most systems use glass mirrors that continuously track the position of the sun. The four major concentrating solar power (CSP) technologies are parabolic trough, Fresnel mirror reflector, power tower, and dish engine. The primary aim of CSP plants is to generate electricity; however, a number of configurations enable CSP to be combined with various desalination methods. The parabolic trough system is currently the best candidate for CSP/desalination coupling, and two types of desalination processes, MED and RO, are currently the best candidates for CSP coupling.

5.1.6. CSP/MED

A typical parabolic trough configuration can be combined with a MED system where steam generated by the trough (superheated to around 380 °C) is first expended in a turbine and then used in a conventional manner for desalination. The typical steam temperature for the MED plant is around 70 °C; therefore, there is sufficient energy in the steam to produce electricity before it is used in the MED plant. During the 1990s, a CSP/MED project was carried out at the Plataforma Solar de Almería (PSA) in Spain to demonstrate the technical feasibility of solar thermal seawater desalination. A more recent project, AQUASOL, was initiated in 2002 to improve the existing system. AQUASOL's objective is to develop a less costly and more energy-efficient seawater desalination technology based on the MED process with zero brine discharge. This is a mature technology, but it cannot currently compete economically with other conventional desalting technologies without further improvements [57,58]. Fig. 10 show a schematic of CSP/MED coupling.

5.1.7. CSP/RO

The heat generated by the CSP plant can be used to produce the electric power needed to drive the RO pumps. Based on internal studies by Bechtel Power Corp. [58], engineers concluded that CSP/RO coupling is more efficient and requires less energy than CSP/MED coupling. Fig. 11 shows a schematic diagram of CSP/RO coupling.

5.2. Solar-photovoltaic-coupled desalination

A photovoltaic cell is semiconductor device that converts sunlight into DC electricity. The most common materials currently used for PV cells are crystalline silicon (mono- or poly-crystalline silicon) and thin-film material (mainly amorphous

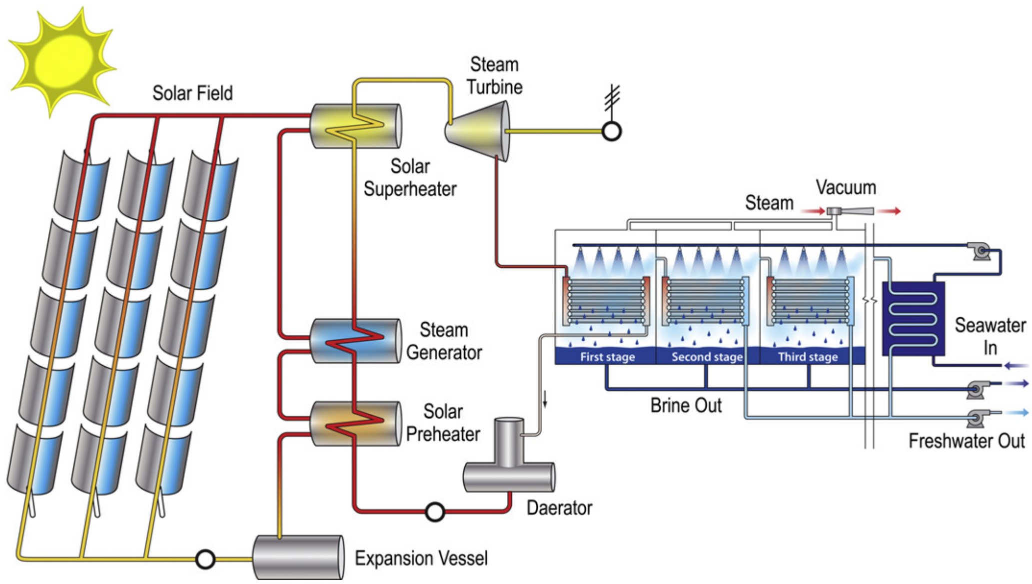

Fig. 10. Schematic diagram of CSP/MED system.

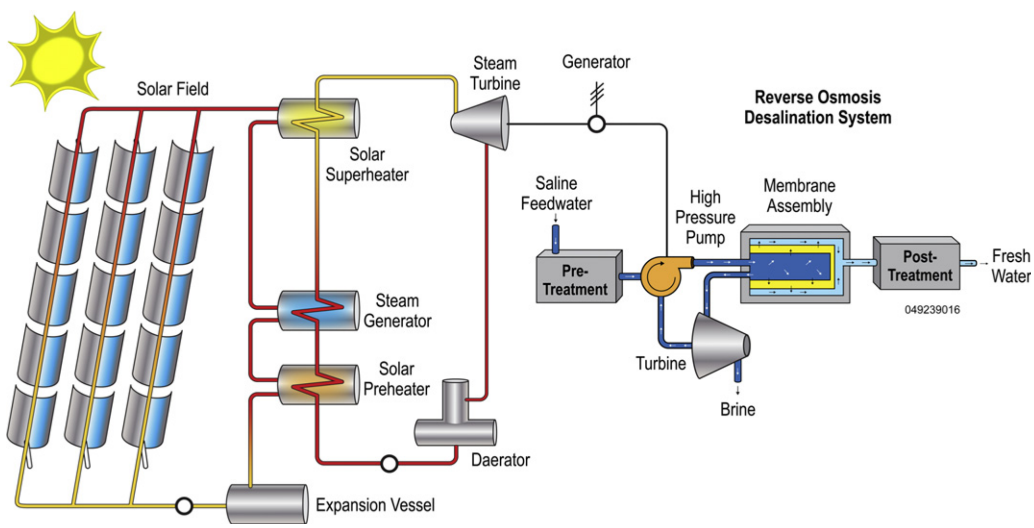

Fig. 11. Schematic diagram of CSP/RO coupling.

silicon). Other thin-film solar cells with efficiencies higher than amorphous silicon are manufactured from materials such as cadmium telluride (CdTe) and copper indium diselenide (CIS). A number of solar cells are usually interconnected and encapsulated together to form a PV module. Any number of PV modules can be combined to form an array, which will supply the power required by the load. In addition to the PV module, power-conditioning equipment (e.g., charge controller, inverters) and energy storage equipment (e.g., batteries) may be required to supply energy to a desalination plant. Charge controllers are used to protect the batteries from overcharging. Inverters convert the direct current produced by the PV system to alternating current to supply the load. PV is a mature technology with modules having a life expectancy of 20 to 30 years. A PV system could be used to power RO and ED desalination units.

5.2.1. PV/RO system

PV-powered reverse osmosis is considered one of the most-promising forms of renewable-energy-powered desalination, especially when used in remote areas. Hence, small-scale PV/RO has received much attention in recent years and numerous demonstration systems have been built. Two types of PV/RO systems are available in the market: PV/BWRO and PV/SWRO systems. Low pressure is needed to desalinate brackish water; therefore, only a small amount of electricity is needed. Many PV/RO projects have been installed around the world, and a number of these use batteries or energy backup to run the system 24 h a day. Consequently, the cost of water production tends to be high [59–64]. Fig. 12 shows a schematic diagram of a PV/RO system.

5.2.2. PV/ED (EDR) system

ED uses DC electricity for the electrodes at the cell stack, and hence, it can use the energy supply from the PV system without major modifications by using an inverter. Also, for water circulation, the ED system needs a low-pressure pump, which could be a DC or AC pump [65]. PV/ED is the most competitive at low-concentration brackish water (less than 2500 ppm). Fig. 13 shows a schematic diagram of a PV/ED system.

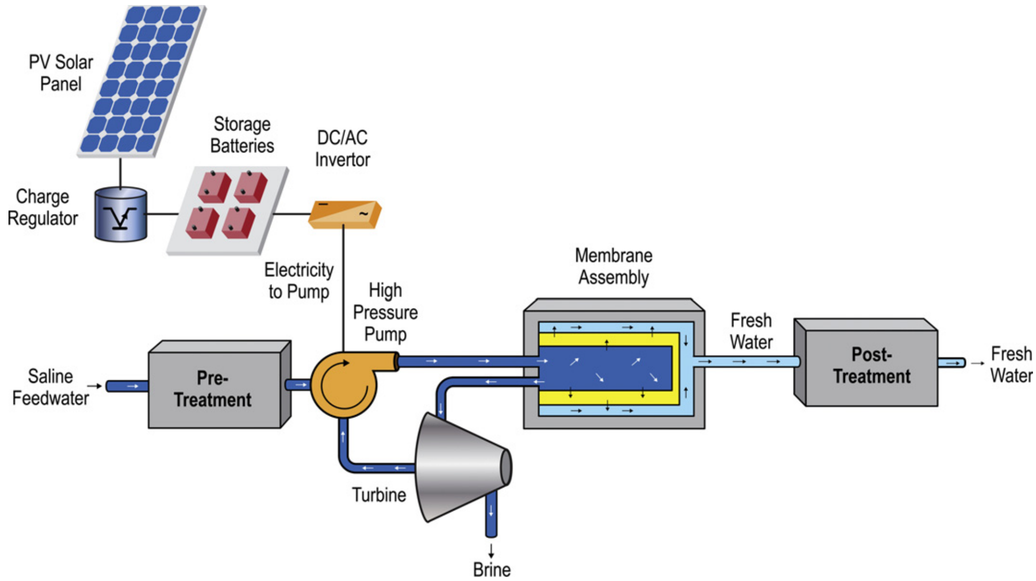

Fig. 12. Schematic diagram of PV/RO system.

5.3. *Wind-coupled desalination*

Wind turbines convert air movement into rotational energy to produce mechanical power or drive a generator to produce electrical power. A distinction can be made between turbines driven mainly by drag forces or by lift forces, and also, between axes of rotation parallel to the wind direction (horizontal-axis wind turbine, HAWT) or with axes perpendicular to the wind direction (vertical-axis wind turbine, VAWT). All modern wind turbines are VAWT driven by lift forces. The fluctuation of wind speed requires a control system that matches the available wind power to the electricity requirement of the desalination unit and dumps the extra wind energy resulting from very high speed to achieve a stable operation. A battery system is normally coupled to smooth the operation. Wind energy could be used to power RO, ED, and MVC, but most applications are wind/RO. The high fluctuation in wind power requires a control system. This system fits the available wind power to the power required for desalination and dumps the surplus energy at very high wind speed to smooth the desalination system operation. A hybrid system of wind/PV is usually used in remote areas.

5.3.1. *Wind/RO system*

Wind power is an excellent candidate for powering a desalination unit, especially in remote areas with suitable wind speed. Excellent work on wind/RO systems has been done by the Instituto Tecnologico de Canarias (ITC) within several projects such as AERODESA and SDAWES (Sea Desalination Autonomous Wind Energy System). The SDAWES project installed eight RO units of 25 m^3/day capacity each with specific consumption of 7.2 kW h/m^3. Additionally, a wind/RO system without energy storage was developed and tested within the JOULE Program (OPRODES-JORCT98-0274) in 2001 by the University of Las Palmas. The typical capacity of the implemented wind/RO units ranged from 50 to 2000 m^3/day [66–71].

5.3.2. *Wind/MVC system*

Wind energy can drive a mechanical compressor or electricity-driven compressor. Few applications have been implemented using wind energy to drive a mechanical vapor-compression unit. A pilot plant was installed in 1991 at Borkum, an island in Germany, where a wind turbine with a nominal power of 45 kW was coupled to a 48 m^3/day MVC evaporator. A 36-kW compressor was required. Additionally, a 50 m^3/day wind MVC plant was installed in 1999 by the ITC in Gran Canaria, Spain, within the SDAWES project. The project consists of a wind farm and several desalination plants. The wind farm is composed of two 230-kW wind turbines, a 1500-rpm flywheel coupled to a 100-kVA synchronous machine, an isolation transformer located in a specific building, and a 7.5-kW uninterruptible power supply located in the control dome. The desalination plant is composed of one 50 m^3/day MVC unit working at 0.2 bar with a specific consumption of 16 kW h/m^3, and a variable-speed compressor at 8400 to 12,000 rpm, in addition to the eight RO units (25 m^3/day each) and one EDR unit with a capacity of 190 m^3/day with a specific consumption of 3.3 kW h/m^3 [66–71].

5.4. *Geothermal-coupled desalination*

Geothermal energy harnesses the heat energy present beneath the earth's surface. The earth's temperature varies widely, and geothermal energy is usable for a wide range of temperatures from room temperature to well over 150 °C. The main advantage of geothermal energy is that thermal storage is unnecessary. Geothermal reservoirs are generally classified as being either low temperature ($<$150 °C) or high temperature ($>$150 °C). Generally speaking, high-temperature reservoirs are the most sought for commercial production of electricity. Energy from the earth is usually extracted with ground heat exchangers, made of an extraordinarily durable material that allows heat to pass through it efficiently. The direct use of moderate and high temperatures is for thermal desalination technologies. A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, whereas high-temperature geothermal fluids can be used to power electricity to drive RO, ED, and MVC plants. Thermal distillation techniques based on direct heating from geothermal energy is the method of choice in most desalination plants. The first desalination plant powered by geothermal energy was constructed in 1972 in the USA, followed by plants in France, Tunisia, and Greece. In 2000, a pilot geothermal/MED plant with a capacity of 80 m^3/day was installed in Kimolos Island and operates at 61 °C with a two-stage MED unit [72–77].

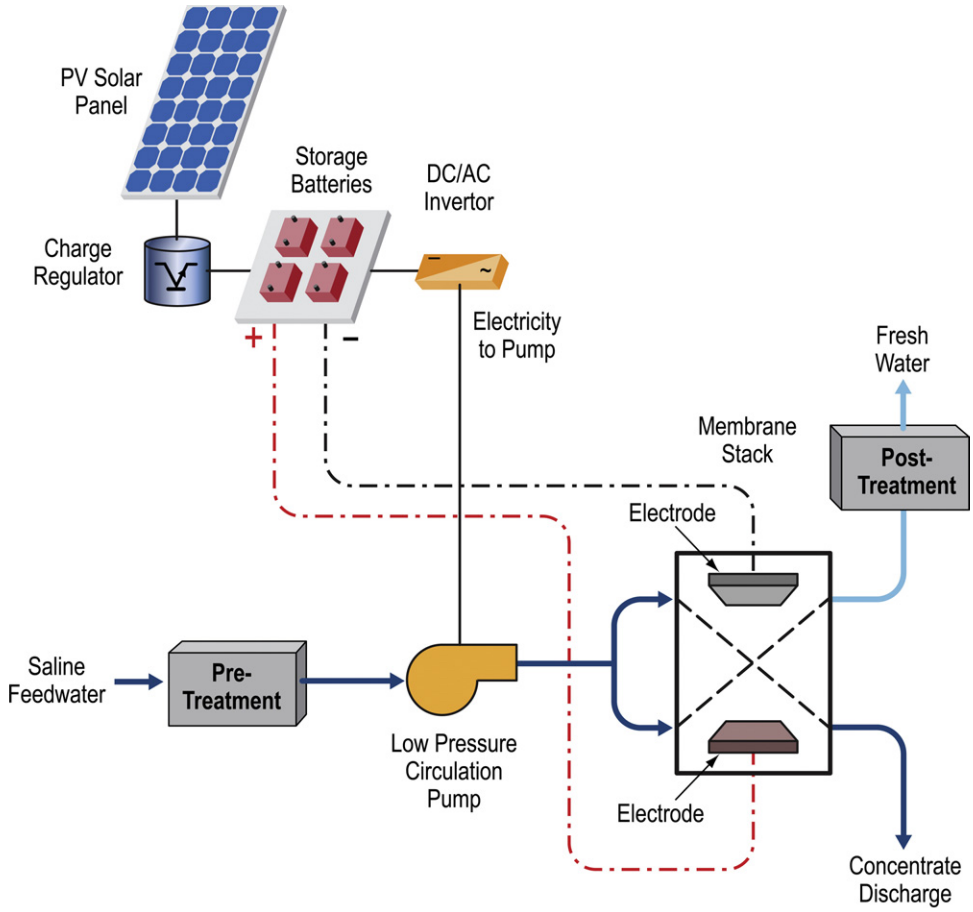

Fig. 13. Schematic diagram of PV/ED system.

6. Economics of renewable-energy-coupled desalination

The cost of water produced from desalination units coupled with renewable energy resources is highly related to the cost of energy produced from these resources. Despite the free cost of renewable energy, the capital cost of renewable energy systems is still very high, this makes the produced water cost high. But with further technology development of renewable energy, the capital cost will be reduced and the water production cost from these resources will also decrease. The economics of each renewable energy desalination coupling will be briefly discussed, and Table 3 presents the average reported water production cost.

6.1. Solar thermal desalination

6.1.1. Solar still

The solar still technology is very simple, the capital cost is low, and there is no need for fossil fuel to evaporate the water. However, the water production cost is very high due to the low productivity of the still. The reported average daily production rate of the still ranges from 4 to 6 l/m^2, and the water cost ranges between 1.3 and 6.5 US\$/m^3 [78].

6.1.2. Solar multi-effect humidification

Low-temperature heat and electricity is required in the MEH unit. The size of implemented MEH units range from 1 to 100 m^3/day, and the average total energy consumption (thermal and electrical) is about 31.1 kW he/m^3. The reported water production cost ranges from 2.6 to 6.5 US\$/m^3 [78].

6.1.3. Solar membrane distillation

Due to the typical low capacity (0.15 to 10 m^3/day) and high energy consumption (150 to 200 kW hth/m^3) of the implemented MD system, it is not yet commercially available in the market. The current water production cost of this system ranges from 10.5 to 19.5 US\$/m^3 [52–56,78].

6.1.4. Solar pond desalination

The temperature of the storage zone of the solar pond could reach above 90 °C. This energy could be used to provide low heat to both MED and MSF desalination and could also be used to generate electricity for RO or ED units. The reported cost of the product water from the implemented SP/MED units ranges from 0.71 to 0.89 US\$/m^3 [49,53,78].

6.1.5. CSP coupled to desalination processes

Using CSP systems with desalination is still in the experimental stage and not commercially implemented. The reported prospective water production cost of this system ranges from 2.4 to 2.8 US\$/m^3 [57,58,78].

6.2. Solar PV desalination

Investment cost is relatively high in PV powered desalination units which results in high water production cost. Two types of systems are commonly applicable in this area. These are PV/RO and PV/ED systems.

Table 3
Energy consumption and water production cost of RE-coupled desalination. *Sources*: Refs. [49–78].

RE-desalination process	Typical capacity (m^3/day)	Energy demand (kW he/m^3)	Water production cost (US$/$m^3$)
Solar still	< 100	Solar passive	1.3–6.5
Solar MEH	1–100	Thermal: 29.6 Electrical: 1.5	2.6–6.5
Solar MD	0.15–10	45–59	10.5–19.5
Solar pond/MED	20,000–200,000	Thermal: 12.4–24.1 Electrical: 2–3	0.71–0.89
Solar pond/RO	20,000–200,000	Seawater: 4–6 Brackish water: 1.5–4	0.66–0.77
Solar CSP/MED	> 5,000	Thermal: 12.4–24.1 Electrical: 2–3	2.4–2.8
Solar PV/RO	< 100	Seawater: 4–6 Brackish water: 1.5–4	11.7–15.6 6.5–9.1
Solar PV/EDR	< 100	1.5–4	10.4–11.7
Wind/RO	50–2,000	Seawater: 4–6 Brackish water:1.5–4	6.6–9.0 small capacity 1.95–5.2 for 1000 m^3/d
Wind/MVC	< 100	7–12	5.2–7.8
Geothermal/MED	80	Thermal: 12.4–24.1 Electrical: 2–3	2–2.8

6.2.1. *PV/RO system*

This technology has been widely used in rural areas of most countries around the world, but mostly with small-size systems, which resulted in high cost of water production. According to published reports [51–56], the reported cost of a SWRO system ranges from 7.95 to 29 US$/$m^3$ for units with capacity of 120 to 12 m^3/day. A new study [61] reported that the cost of fresh water ranges from 11.7 to 15.6 US$/$m^3$ for SWRO small-capacity systems (< 100 m^3/day). For a BWRO system, the cost ranges from 6.5 to 9.1 US$/$m^3$.

6.2.2. *PV/ED system*

Only a few pilot plants of PV/ED units are implemented in several countries. These units have capacities of less than 100 m^3/day and are mostly for R&D purposes. The water production cost of these systems range from 5.8 to 16 US$/$m^3$ [65,78].

6.3. *Wind desalination*

Wind energy could be used to drive RO, ED, and VC desalination units. Most available applications are for the stand-alone wind-driven RO system, which is mostly implemented in remote areas.

6.3.1. *Wind/RO system*

A large number of medium (1000 to 2500 m^3/day) and small (< 100 m^3/day) wind/RO systems have been designed and tested in different parts of the world. The water production cost of the medium-size systems ranges from 1.8 to 5.2 US$/$m^3$. For small-size systems, water production cost ranges from 3.9 to 9.1 US$/$m^3$ [66–71,78].

6.3.2. *Wind/MVC system*

Wind could be used to drive the compressor of the MVC system mechanically or electrically. Small capacity (< 100 m^3/day) systems have been tested and analyzed. The reported water production cost ranged from 5.2 to 7.8 US$/$m^3$ [66–71,78].

6.4. *Geothermal desalination*

Geothermal energy can provide both thermal energy and electricity; therefore, all types of desalination processes can be coupled with this resource. Geothermal energy can provide heat to MSF, MED, and TVC and electricity for RO, ED, and MVC. From the experience of different projects implemented in the USA, France, Tunisia, and Greece, it is estimated that a geothermal source with a temperature of 80° to 100 °C can produce fresh water at a cost of 2 to 2.8 US$/$m^3$ [72–78].

7. Environmental impacts of water desalination

The three environmental impacts most commonly associated with water desalination are the (1) large amount of hot-gas emission resulting from intensive energy consumption, (2) quantity and temperature of the discharged concentrated brine, and (3) discharge of chemicals used in the pretreatment.

All desalination technologies are energy-intensive processes that result in the emission of a huge amount of greenhouse gases that include CO, CO_2, NO, NO_2, and SO_2. The amount of CO_2 is estimated to be 25 kg/m^3 of product water [79,80]. The use of renewable energy resources is an excellent solution to overcome the harmful gases emission.

Concentrate is the byproduct of desalination. It is generally a liquid substance with very high concentration. The salinity of the discharge from RO plants is about 100% higher than the seawater salinity, but at ambient temperature, whereas the salinity of the discharge from distillation (MSF or MED) plants is about 15% higher than the seawater at a temperature of 5° to 10 °C higher than the ambient. Therefore, distillation plants have a greater negative impact on and more risks to the marine and aquatic life because higher temperature reduces the overall concentration of dissolved oxygen in the receiving waters, excluding life that cannot exist at low oxygen levels.

The RO process requires more intensive pretreatment than distillation processes. This pretreatment is in the form of chemical additives that have direct and indirect impacts on the aquatic marine life. But the level of these chemicals is generally relatively low.

8. Conclusion

Desalination continues to grow due to the increased water scarcity in many parts of the world, the increase in population, and industrial and economic growth. Desalination technologies have been in continuous rapid development during the previous decades in both system design and operation. This led to a huge savings in power consumption and a cost reduction in water

production. In the 1960s, it cost about 10 US$/m^3, whereas currently, the two most-used desalination technologies (RO and MSF) are at less than 0.6 US$/m^3.

The selection of a particular desalination technology is based on several factors, such as specific site condition, type and quality of feed water, energy availability and consumption, economics, and environmental impacts. For seawater, the energy consumption and water production cost of the RO process is lower than all distillation processes (MSF, MED and VC). This is due to technological advances in membrane manufacturing, high efficiency in the recovery equipment, higher efficiency in pumps, better control of scaling, and improvements in the process. For brackish-water desalination, the two most-economic methods are RO and ED. RO is generally believed to be more cost effective when TDS is more than 5000 ppm, whereas ED is more cost effective for TDS feed concentrations less than 5000 ppm.

All desalination processes have a negative impact on the environment due to their intensive consumption of energy and brine disposal. Therefore, using renewable energy to power desalination processes will mitigate some of this impact, although the current water production cost from renewable-energy-coupled desalination systems is much higher than the water cost of conventional desalination systems. However, this high cost is offset by the environmental benefits. Due to this high cost, desalination systems incorporating renewable energy resources are currently only economic in rural areas without access to electric grid, where water scarcity is a major problem, and where solar radiation or wind speed are appropriate. With further technological advances, capital costs will be reduced and reliable, compact renewable energy systems will be available in the market at a reasonable cost, which will lead to a remarkable decrease of the cost of water produced.

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